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Lee

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(54) **HEATING SYSTEM HAVING PLASMA HEAT EXCHANGER**

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(65) **Prior Publication Data**

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Related U.S. Application Data

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(51) **Int. Cl.**

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H05B 3/78	(2006.01)
F24H 1/00	(2006.01)
F24H 1/16	(2006.01)
F24H 1/22	(2006.01)
F24H 1/28	(2006.01)
F24H 9/00	(2006.01)
F24H 9/18	(2006.01)
H05H 1/48	(2006.01)
F28D 7/02	(2006.01)

(52) **U.S. Cl.**

CPC ***F24H 1/0018*** (2013.01); ***F24H 1/162*** (2013.01); ***F24H 1/225*** (2013.01); ***F24H 1/287*** (2013.01); ***F24H 9/0021*** (2013.01); ***F24H 9/1818*** (2013.01); ***F28D 7/024*** (2013.01); ***H05H 1/48*** (2013.01); *F24H 2250/10* (2013.01)

(58) **Field of Classification Search**

None

See application file for complete search history.

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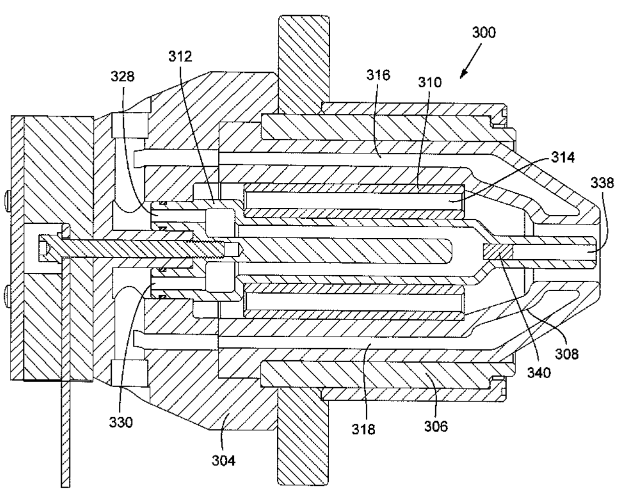
Primary Examiner — Thor Campbell

(74) *Attorney, Agent, or Firm* — Klarquist Sparkman, LLP

(57) **ABSTRACT**

Systems and methods for heating a fluid are disclosed. In certain embodiments, plasma is generated and passed through a conduit. A fluid to be heated can be passed over the conduit, thereby inducing a heat transfer from the plasma to the fluid. In certain embodiments, multiple plasma generators and corresponding conduits are provided and the conduits are positioned within a housing, facilitating a more effective heat transfer. In some embodiments, the plasma generator includes an outer shell, an anode, a cathode, and insulating elements, and generates plasma by passing a gas through an electric arc created between the anode and the cathode.

15 Claims, 22 Drawing Sheets



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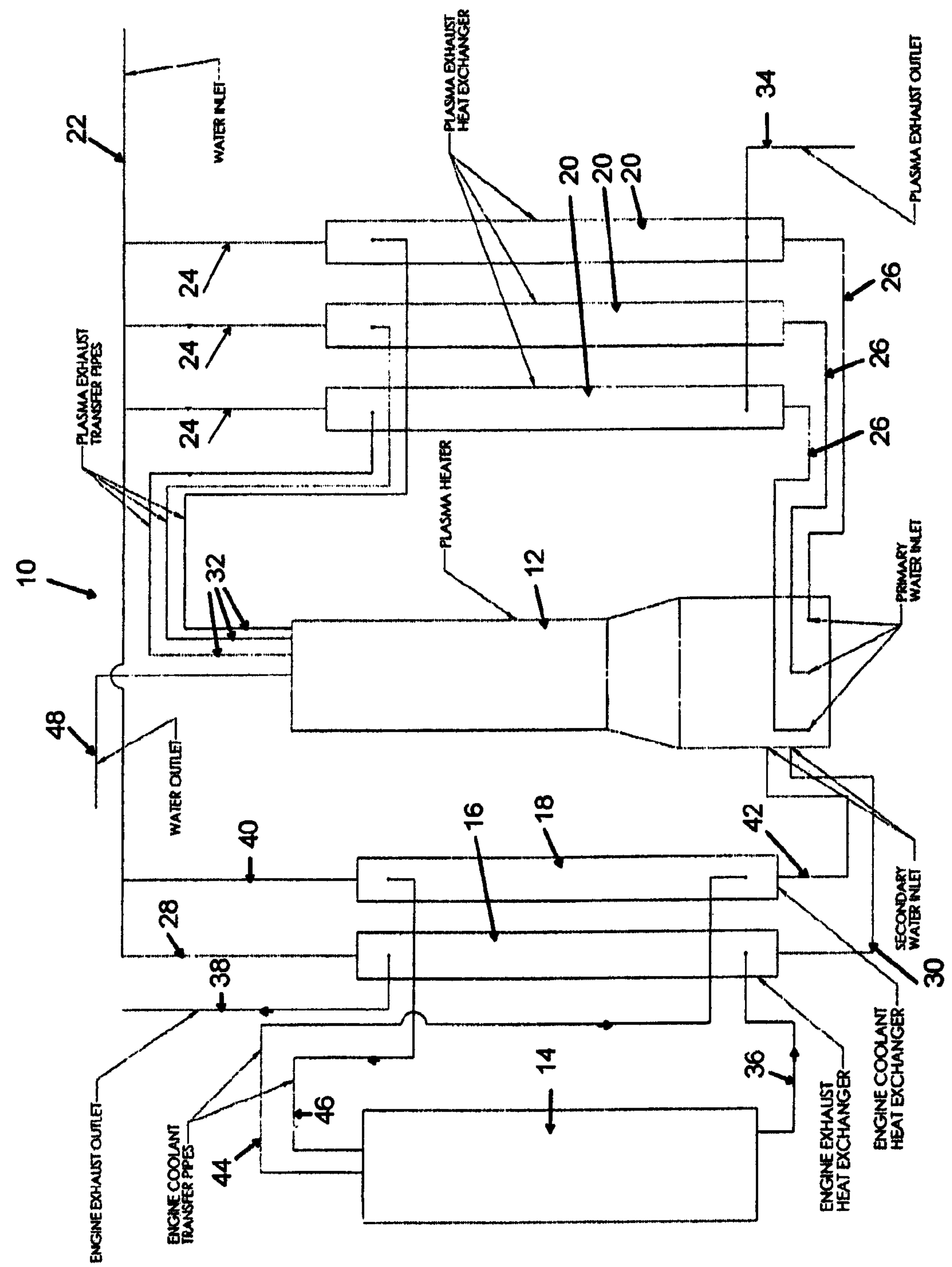
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FIG. 1

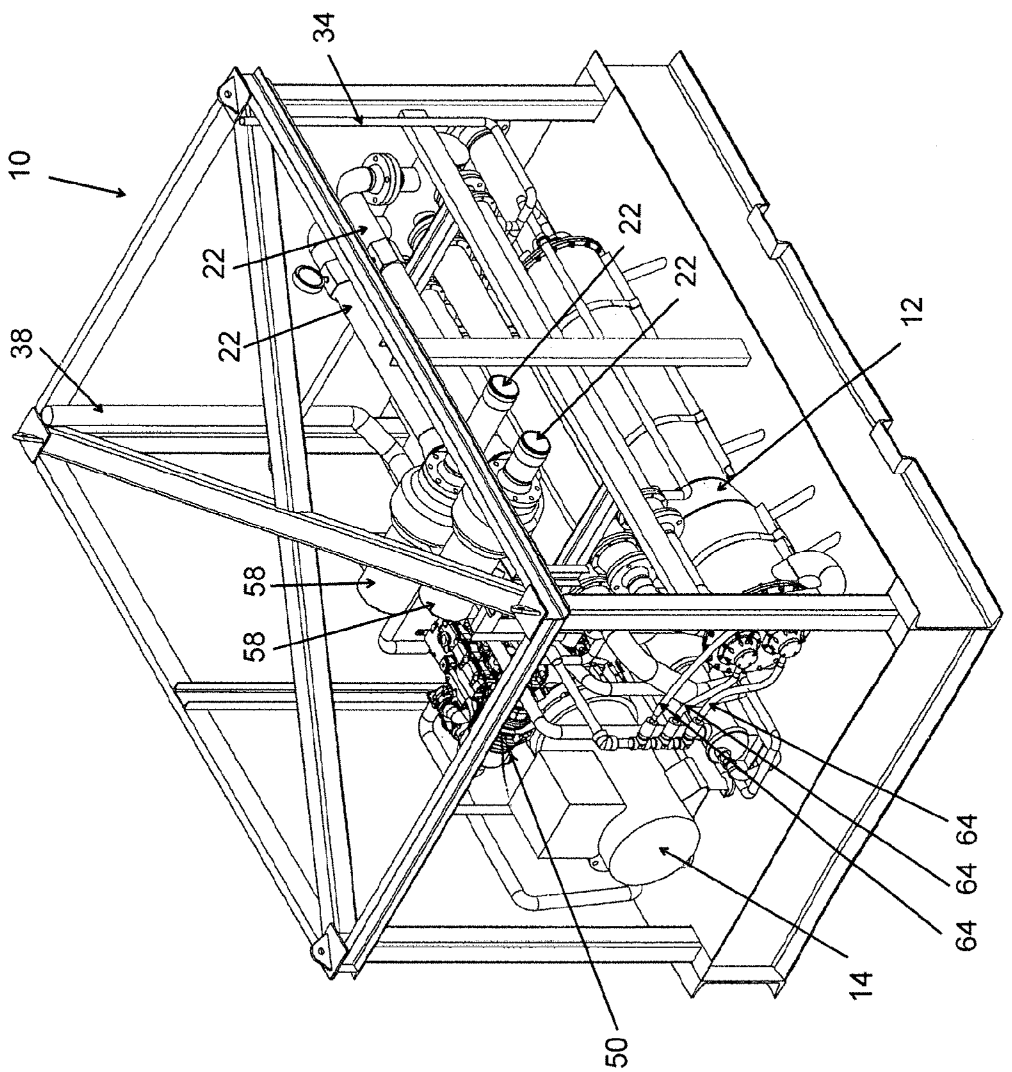


FIG. 2

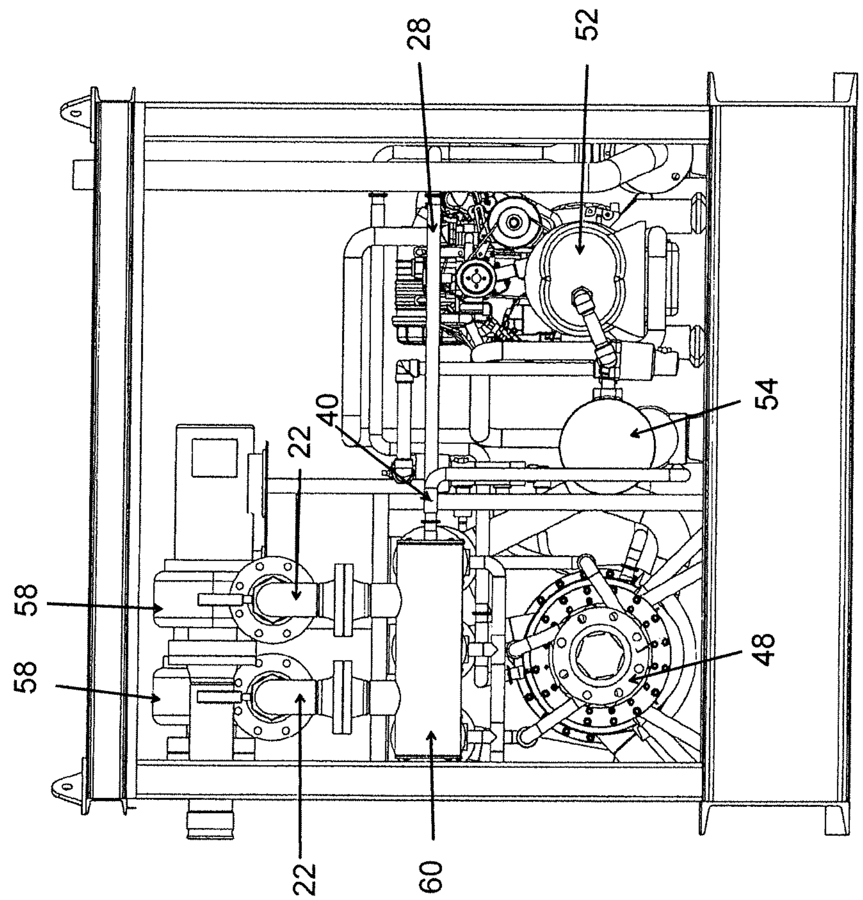
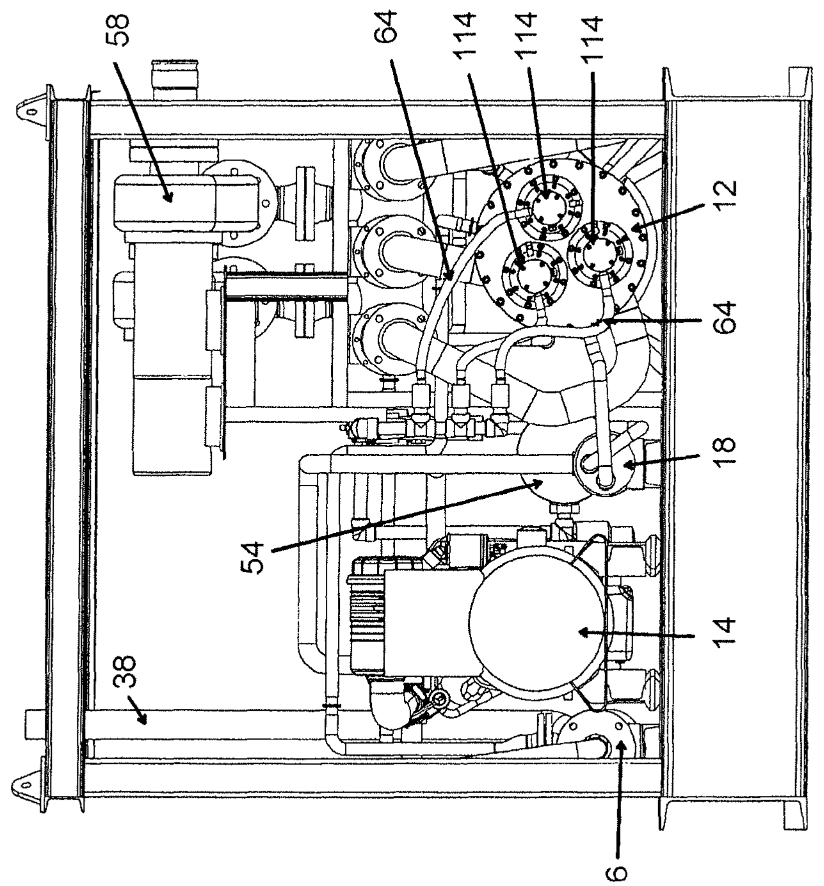


FIG. 3



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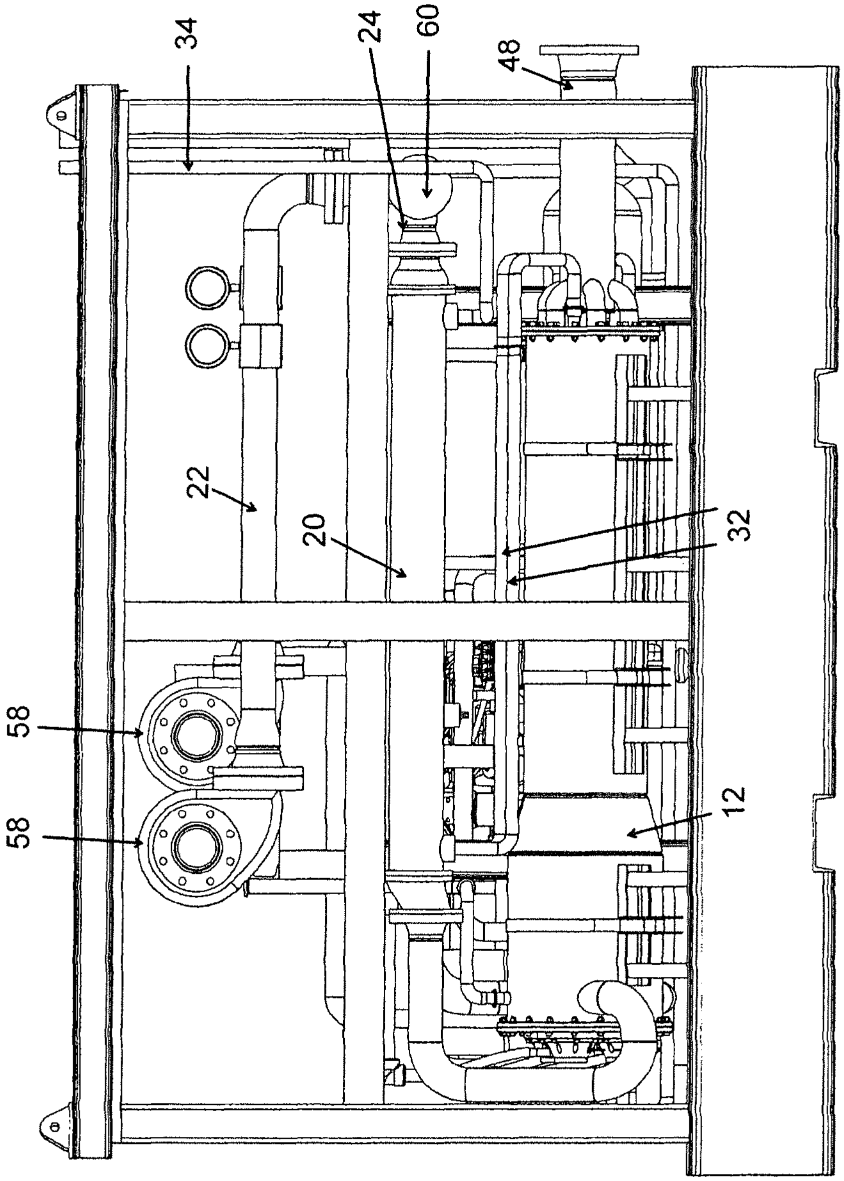

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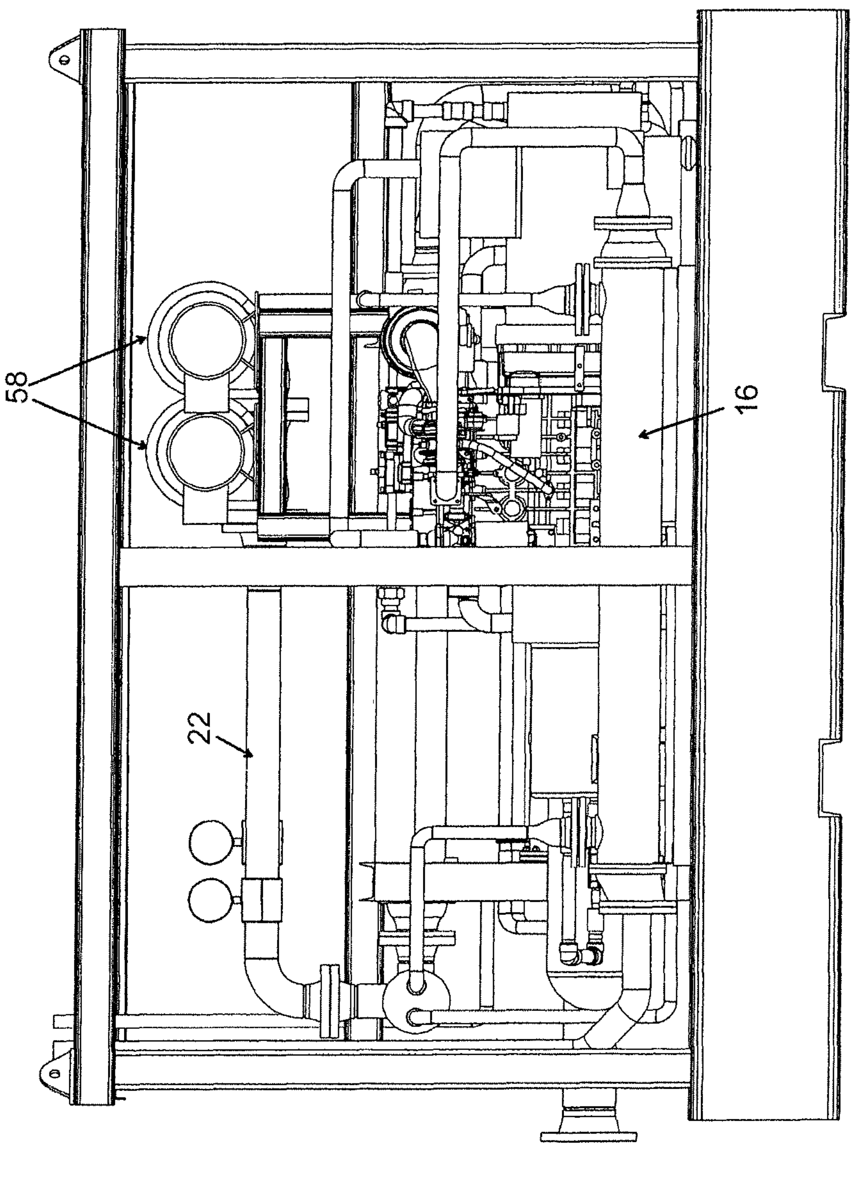

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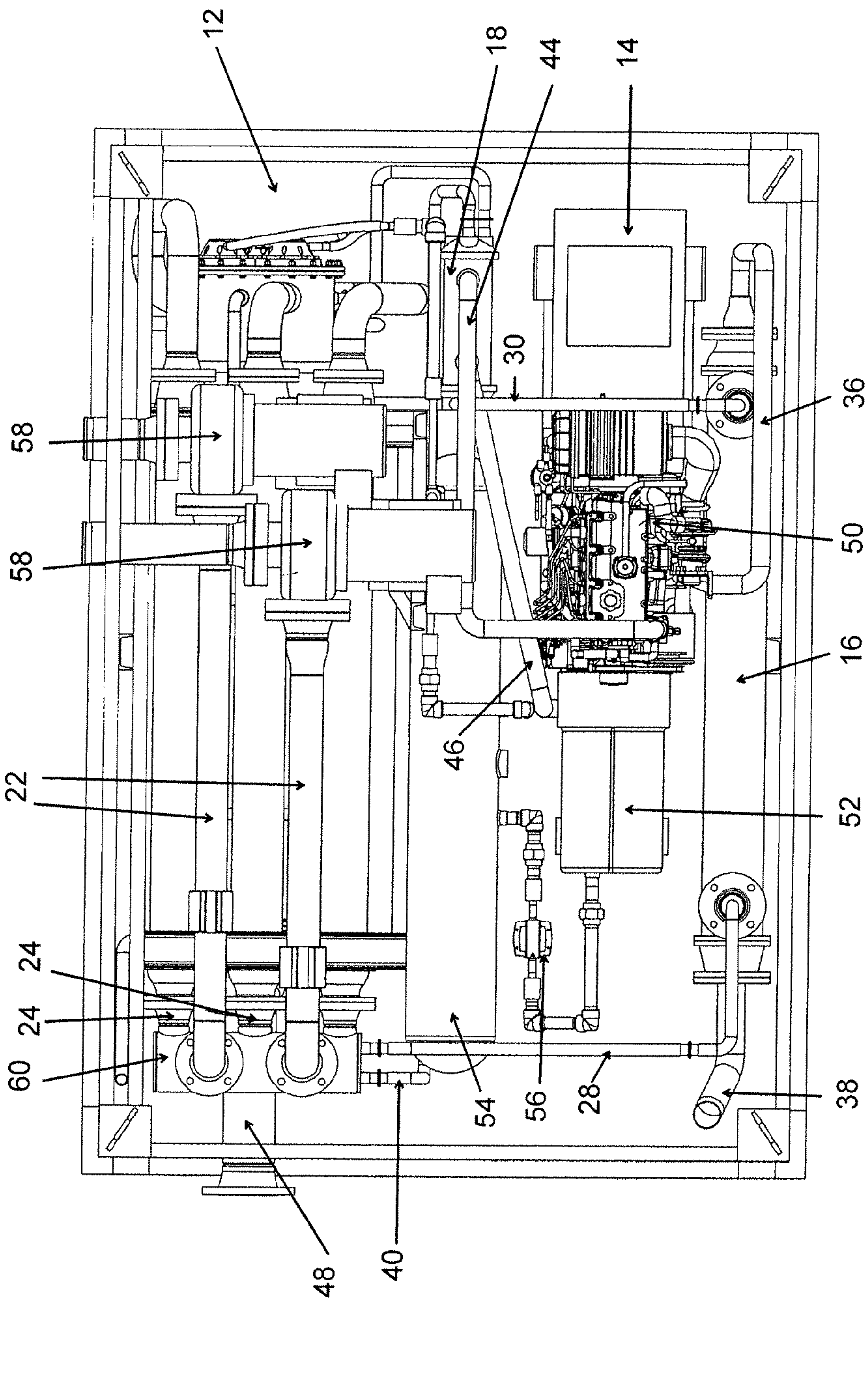

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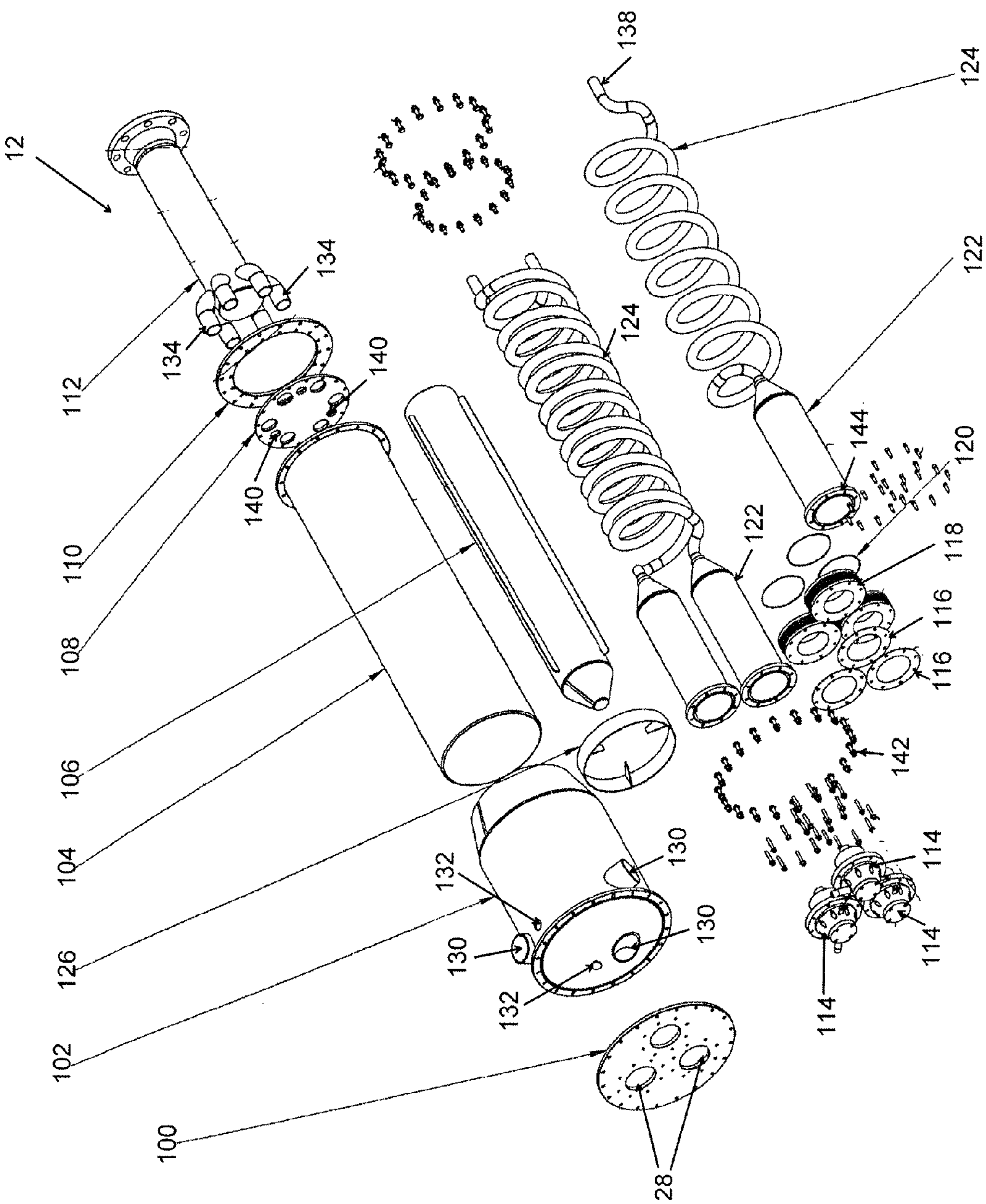
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FIG. 8

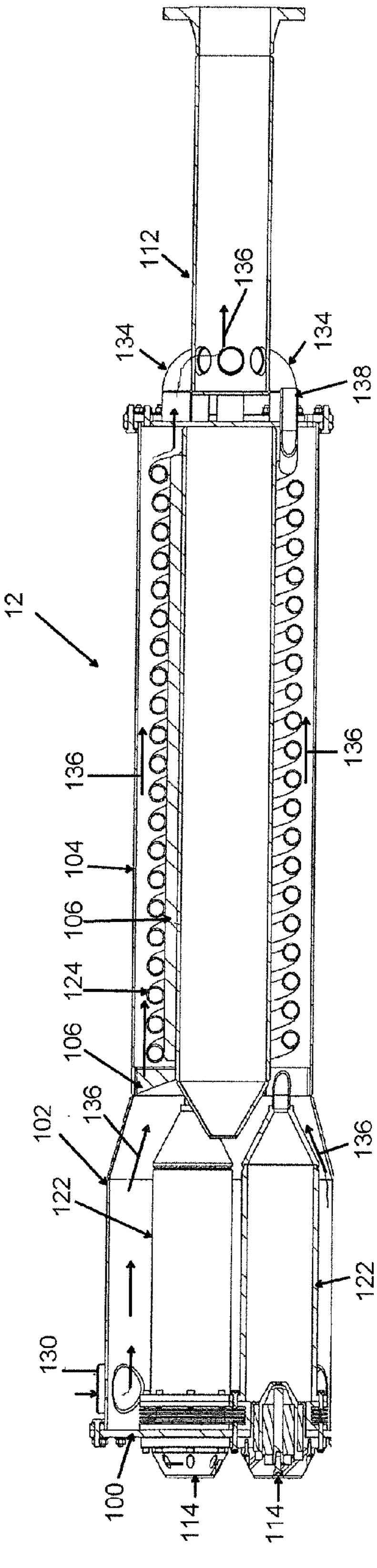
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FIG. 9

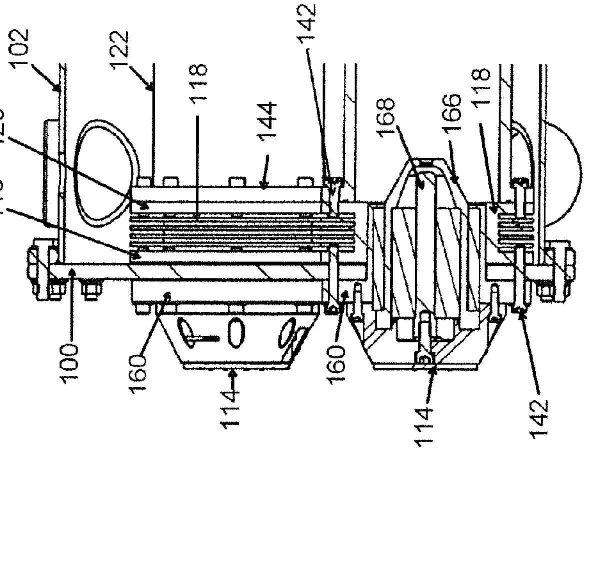
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FIG. 9A

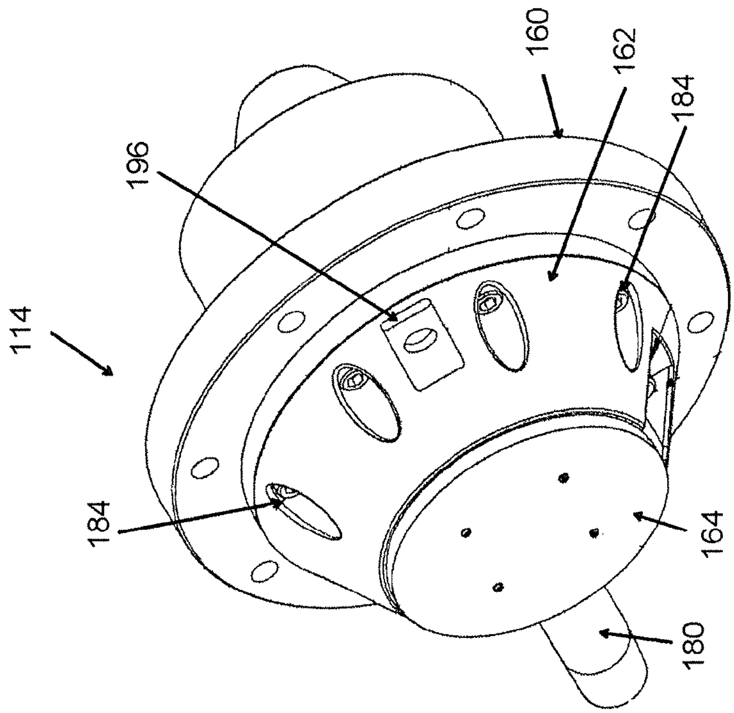
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FIG. 11

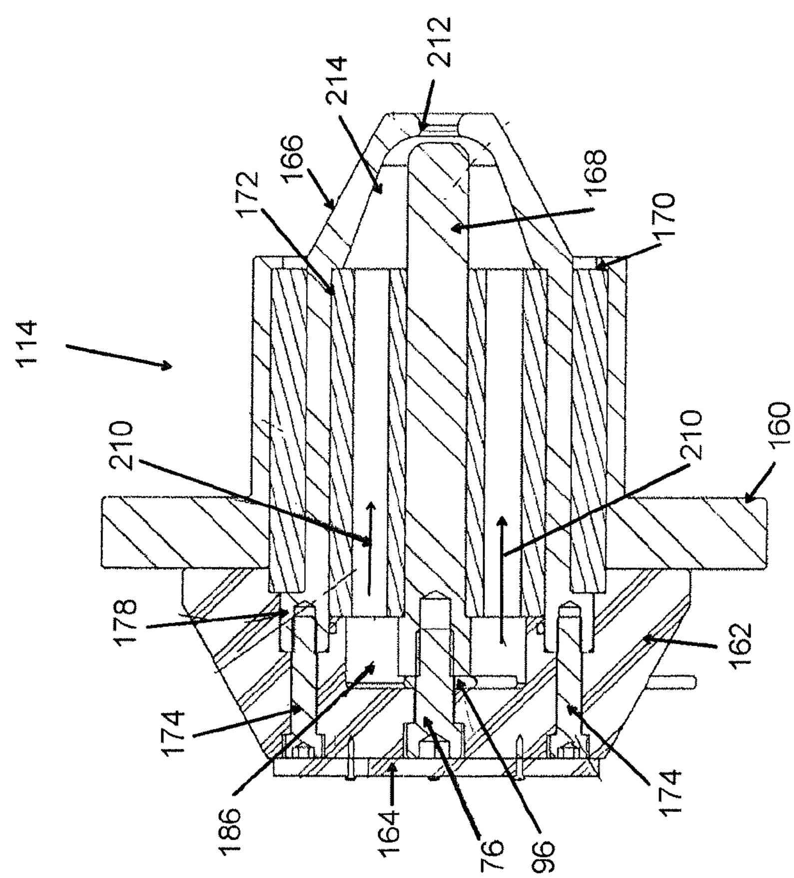
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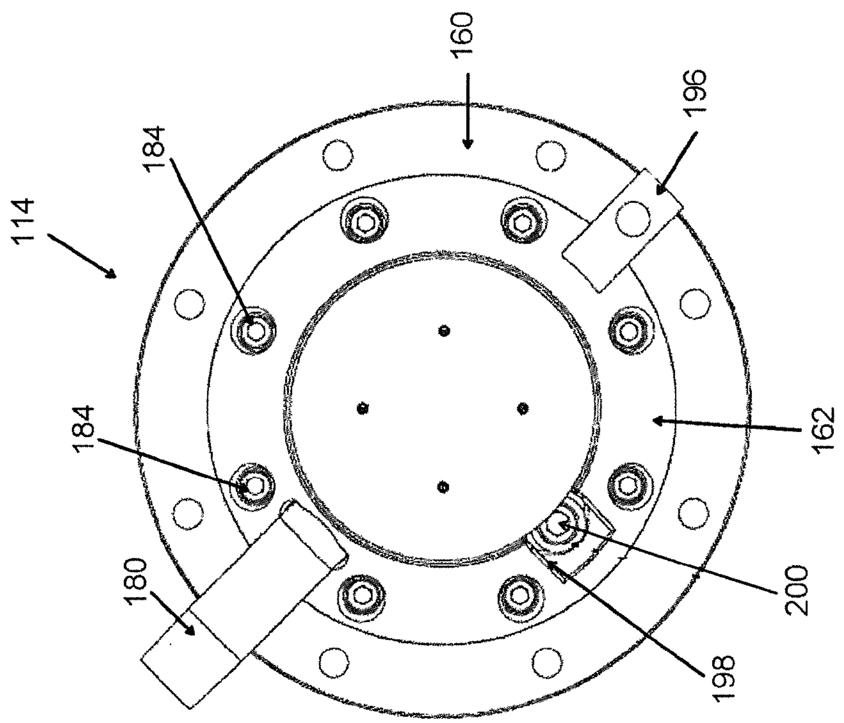
FIG. 10



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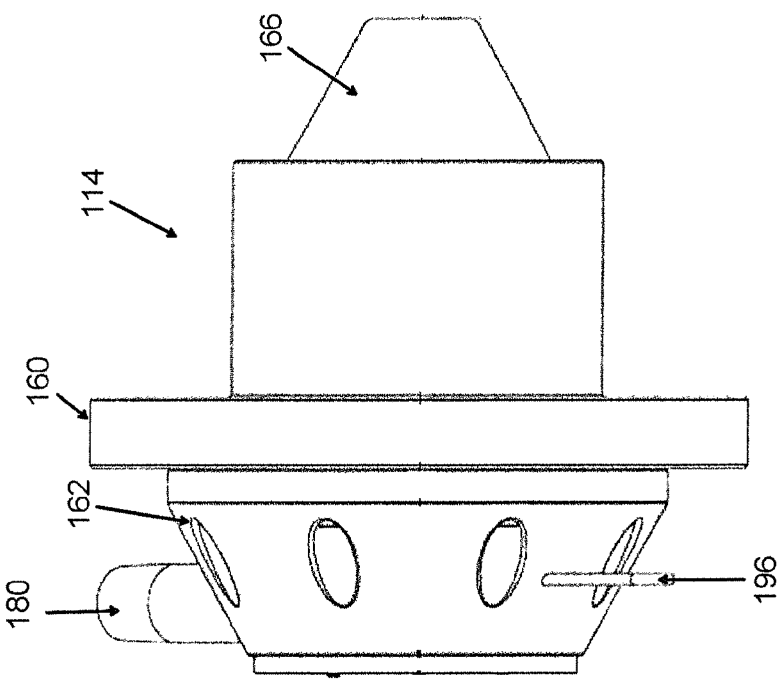

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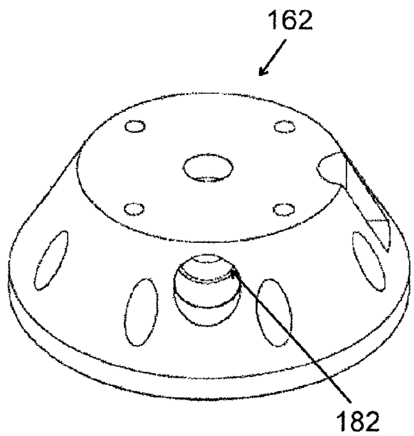

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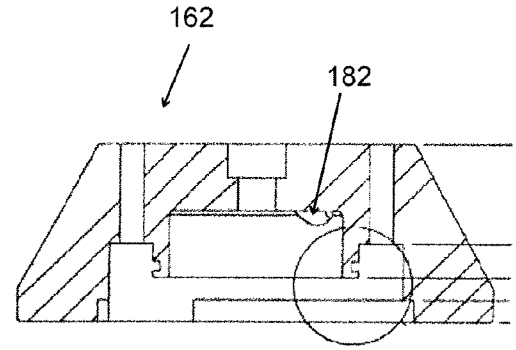

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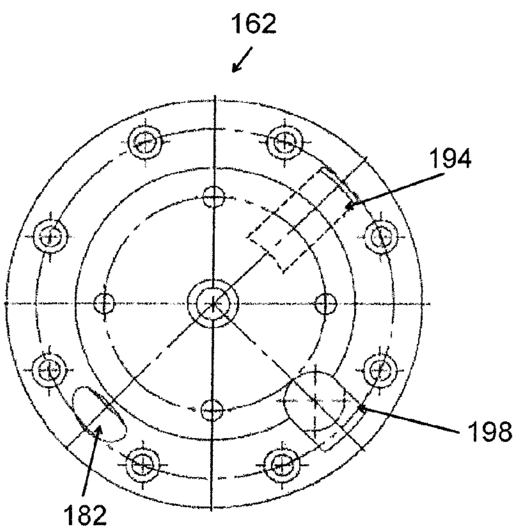

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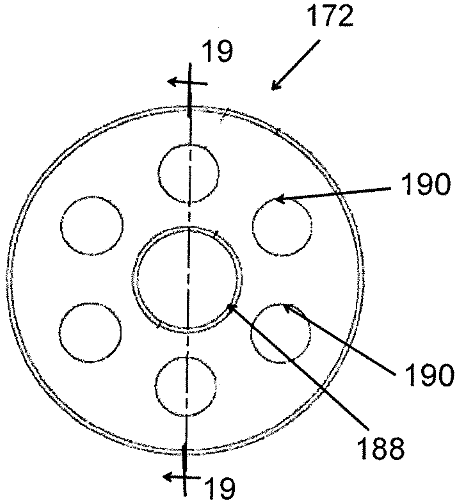

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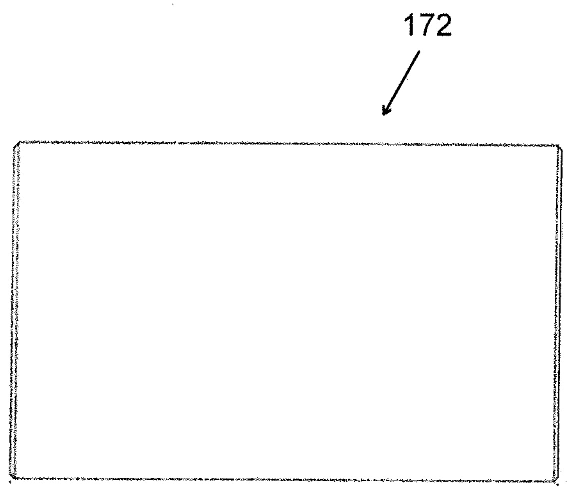

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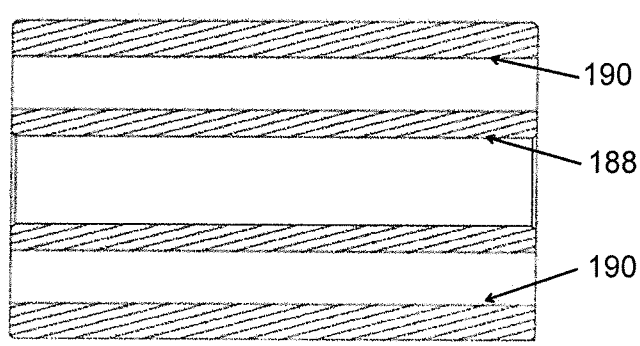


FIG. 19

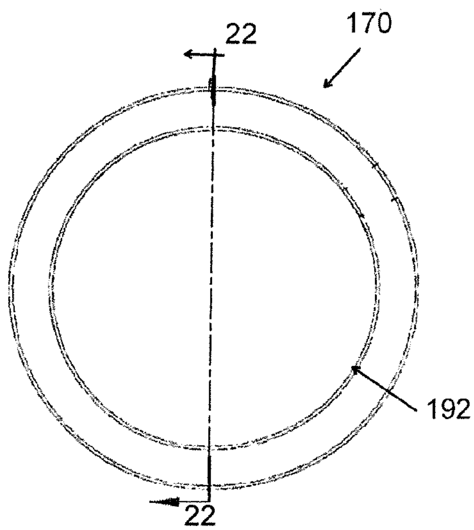
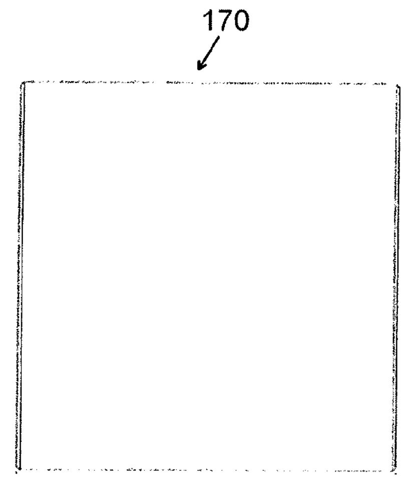


FIG. 20



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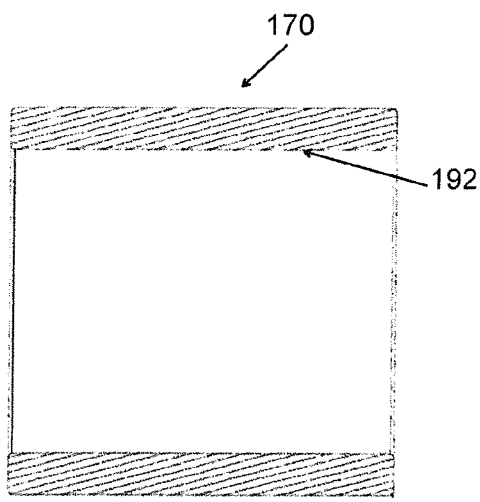

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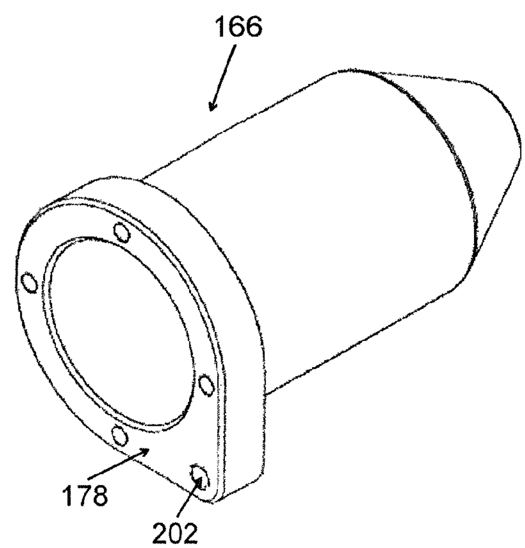

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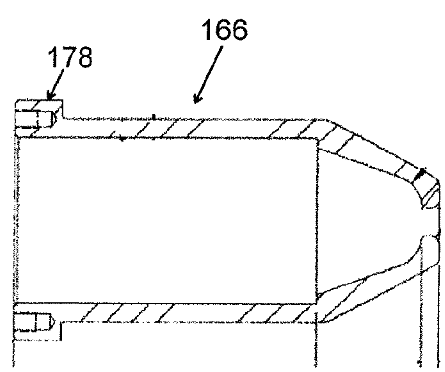

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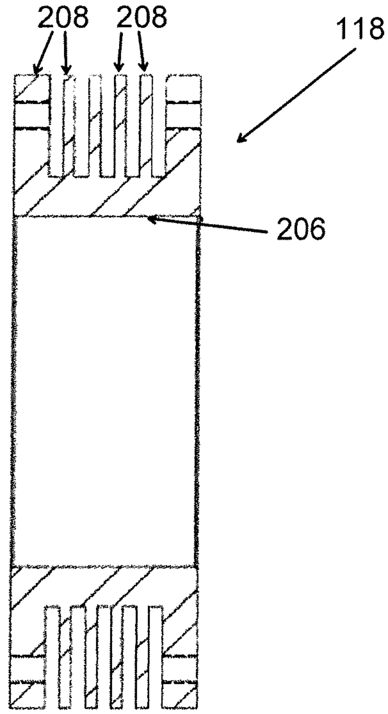

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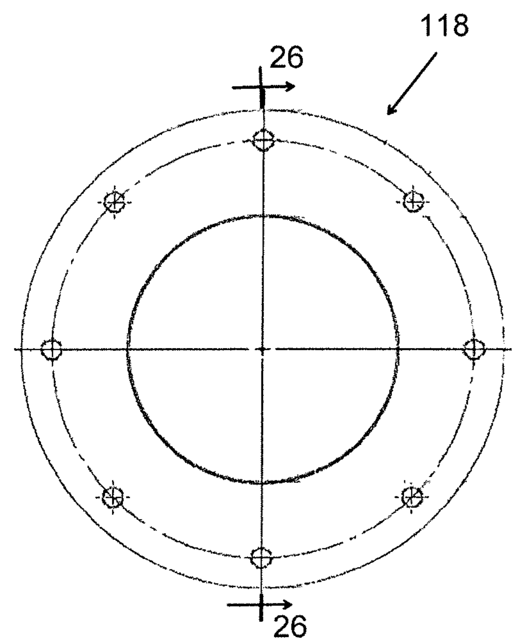
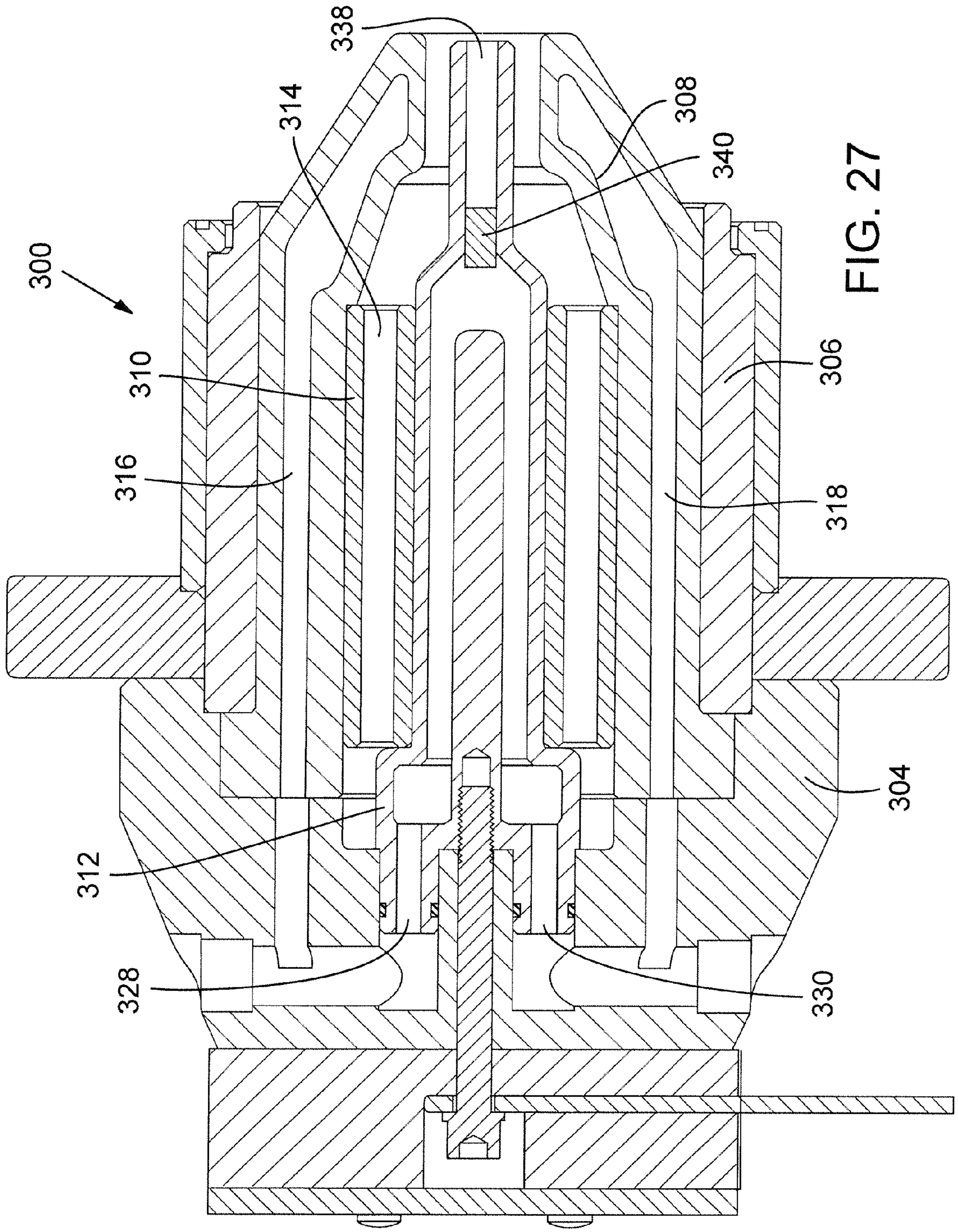


FIG. 25



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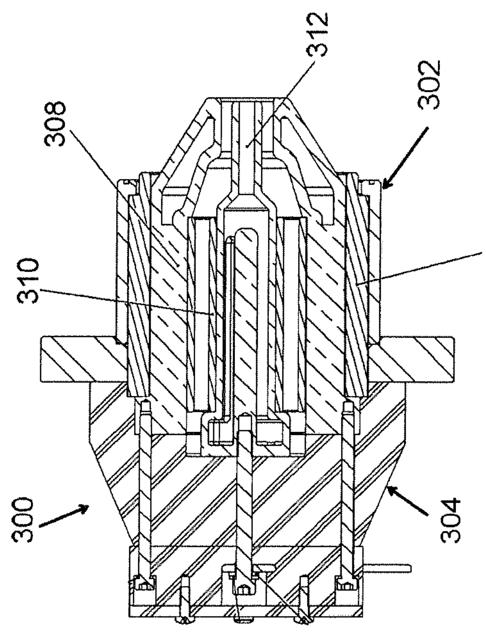

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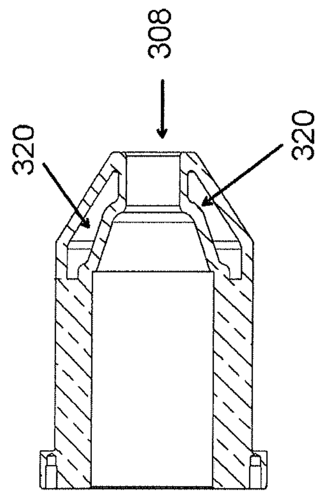

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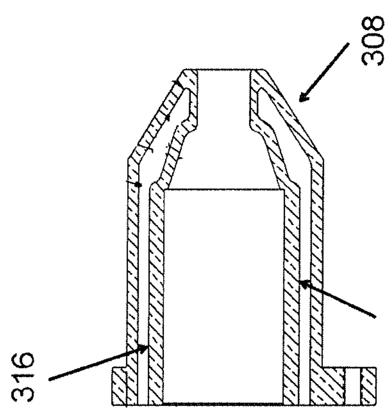

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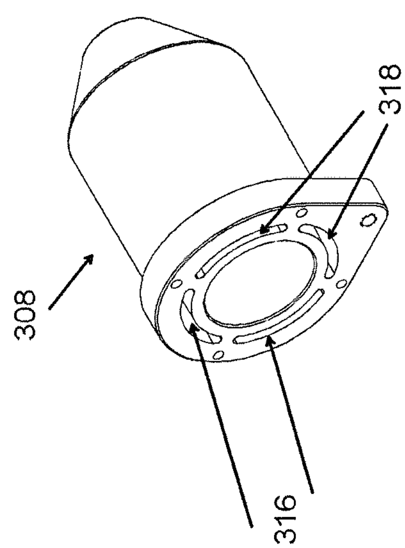

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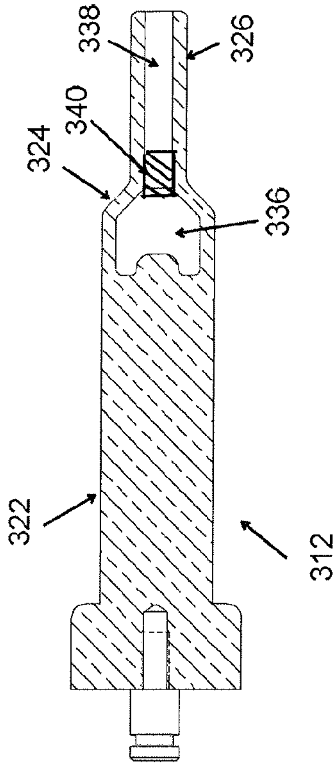
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FIG. 33

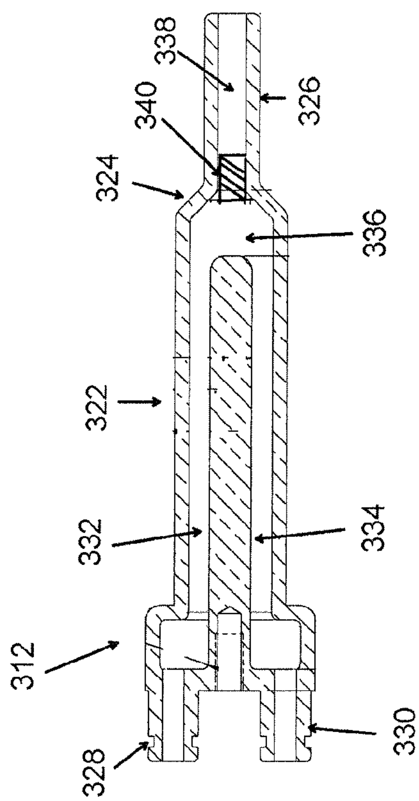
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FIG. 32

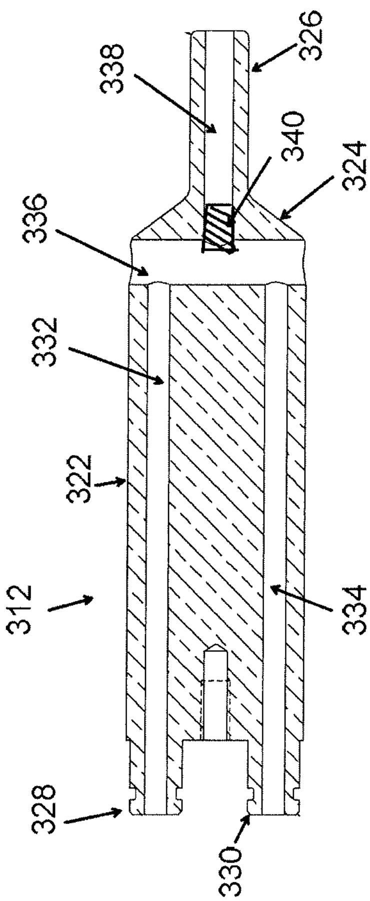

FIG. 34

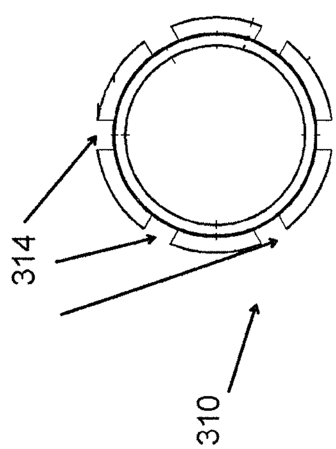

FIG. 35

HEATING SYSTEM HAVING PLASMA HEAT EXCHANGER

CROSS REFERENCE TO RELATED APPLICATION

This application claims the benefit of U.S. Provisional Patent Application No. 61/558,949, filed Nov. 11, 2011, which is hereby incorporated herein by reference.

FIELD

The present disclosure concerns embodiments of a heating assembly that incorporates one or more plasma generators for heating a fluid.

BACKGROUND

A heat exchanger is a device designed to transfer heat from a first substance to a second, thereby decreasing the heat content of the first substance and increasing the heat content of the second. Heat exchangers have various industrial and commercial applications, including use in power plants, refrigerators, automobile radiators, etc., and various configurations of heat exchangers are known in the art. Methods of heating fluids have various specific applications which include heating cleaning fluids for treating a well bore or pipeline, and heating gases or liquids for use in fracking operations. In at least some of these applications, fluid-heating devices may need to be used in remote and/or numerous locations in a short time span. While many configurations of heat exchangers and devices for heating fluids are known, there is always a need for improvements in efficiency, capacity, portability, and other relevant characteristics of these devices.

Plasma is a state of matter distinct from the traditionally known liquid, gas, and solid states. Generally speaking, it is a gas whose particles have been ionized. Plasma can be created by various natural and artificial methods, including by the exposure of a gas to extreme heat and/or magnetic fields. Methods of generating and using plasma include, as examples, plasma globes, plasma television screens, fluorescent lamps, neon signs, and arc welding. In arc welding, an electric current is passed through the air between two spaced apart pieces of conductive material, thereby creating an electric arc (a very high temperature plasma) between them. Thus, in arc welding, an electric current is used to create a high temperature plasma which can heat and melt the materials to be welded.

Accordingly, it would be desirable to provide improved methods of generating high temperature plasma. Additionally, it would be advantageous to provide improved methods and devices for heating fluids utilizing the heat of high temperature plasma. Improvements in efficiency, capacity, and portability of such methods and devices would all be valuable.

SUMMARY

Disclosed herein are embodiments of an invention allowing the generation of high-temperature plasma and its use for heating a fluid by heat exchange. In some embodiments, a plasma generator comprises an anode and a cathode between which an electrical potential difference can be established. A gas, such as air, is passed between the anode and the cathode, and an electric arc (a high temperature plasma) is created between the electrodes and through the gas. The high temperature plasma and/or high temperature exhaust gases can extend through a conduit over which a fluid to be heated flows, thereby allowing a heat exchange between the plasma and the fluid. Certain embodiments provide a coolant to flow within the anode and/or the cathode to protect against overheating. Certain embodiments utilize a plurality of plasma generators and a plurality of conduits. Certain embodiments utilize supplementary heat exchangers which use engine coolant, engine exhaust, or plasma exhaust to pre-heat the fluid to be heated before it flows over the conduit.

In one embodiment, a heating apparatus includes plural plasma generators and plural conduits, each conduit extending from a plasma generator and configured to receive plasma and/or plasma exhaust therefrom. Each conduit can comprise a burn chamber and a coil, with each burn chamber extending from a respective plasma generator and each coil extending from a respective burn chamber. A conduit housing can be provided which surrounds the conduits, and through which a fluid to be heated can flow. In some embodiments, an insert extends through the coils within the conduit housing such that a smaller volume of water passes through the conduit housing.

In another embodiment, a method comprises generating plasma within a burn chamber that is surrounded by a housing. A fluid is allowed to flow through the housing and over the burn chamber, thereby receiving heat from the plasma. The generation of plasma may be cyclical or periodic, such that the plasma generator is not constantly generating plasma. If multiple plasma generators are utilized, their cycles may be coordinated such that plasma is constantly generated by at least one of the generators.

In yet another embodiment, a plasma generator comprises a casing, an outer insulator positioned coaxially within the casing, a cathode positioned coaxially within the outer insulator, an inner insulator positioned coaxially within the cathode, and an anode positioned coaxially within the inner insulator. A difference in electrical potential can be established between the anode and the cathode, and thus an electric arc can be generated when a gas is passed between them. The inner insulator can have air channels extending along its length to allow a gas to be provided to the gap between the electrodes. The cathode and the anode can be provided with ducts or channels for allowing a coolant fluid (e.g., water) to flow through, in order to protect against overheating of the various components. Materials, components, and configurations can additionally be selected to increase the transfer of heat from the electrodes to the coolant fluid to further protect against overheating.

The disclosed embodiments should not be construed as limiting in any way. Instead, the present disclosure is directed toward all novel and nonobvious features and aspects of the various disclosed embodiments, alone or in various combinations and sub-combinations with one another.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic view of a heating assembly for heating a fluid, according to one embodiment.

FIG. **2** is perspective view of a heating assembly for heating a fluid, according to one embodiment.

FIG. **3** is a rear elevation view of the heating assembly of FIG. **2**.

FIG. **4** is front elevation view of the heating assembly of FIG. **2**.

FIG. **5** is a right side elevation view of the heating assembly of FIG. **2**.

FIG. **6** is a left side elevation view of the heating assembly of FIG. **2**.

FIG. **7** is a top plan view of the heating assembly of FIG. **2**.

FIG. **8** is an exploded, perspective view of the plasma heat exchanger incorporated in the heating assembly of FIG. **2**.

FIG. **9** is a cross-sectional view of the plasma heat exchanger of FIG. **8**.

FIG. **9**A is an enlarged view of the forward end portion of the heat exchanger section shown in FIG. **9**.

FIG. **10** is a cross-sectional view of a plasma generator, according to one embodiment.

FIG. **11** is a perspective view of the plasma generator shown in FIG. **10**.

FIG. **12** is a side elevation view of the plasma generator shown in FIG. **10**.

FIG. **13** is a front elevation view of the plasma generator shown in FIG. **10**.

FIG. **14** is an enlarged, perspective view of the air injection cap of the plasma generator shown in FIG. **10**.

FIG. **15** is a cross-sectional view of the air injection cap shown in FIG. **14**.

FIG. **16** is a front elevation view of the air injection cap shown in FIG. **14**.

FIG. **17** is a front elevation view of the inner insulator of the plasma generator shown in FIG. **10**.

FIG. **18** is a side elevation view of the inner insulator shown in FIG. **17**.

FIG. **19** is a cross-sectional view of the inner insulator taken along line **19-19** of FIG. **17**.

FIG. **20** is a front elevation view of the outer insulator of the plasma generator shown in FIG. **10**.

FIG. **21** is a side elevation view of the outer insulator shown in FIG. **20**.

FIG. **22** is a cross-sectional view of the outer insulator taken along line **22-22** of FIG. **20**.

FIG. **23** is a perspective view of the nozzle of the plasma generator shown in FIG. **10**.

FIG. **24** is a cross-sectional view of the nozzle shown in FIG. **23**.

FIG. **25** is a front elevation view of one of the heat sinks of the plasma heat exchanger shown in FIG. **8**.

FIG. **26** is a cross-sectional view of the heat sink taken along line **26-26** of FIG. **25**.

FIGS. **27** and **28** are cross-sectional views of an alternative plasma generator, according to another embodiment.

FIGS. **29** and **30** are cross-sectional views of the cathode of the plasma generator shown in FIGS. **27** and **28**.

FIG. **31** is a perspective view of the cathode of the plasma generator shown in FIGS. **27** and **28**.

FIGS. **32** and **33** are cross-sectional views of one embodiment of the anode of the plasma generator shown in FIGS. **27** and **28**.

FIG. **34** is a cross-sectional view of another embodiment of the anode of the plasma generator shown in FIGS. **27** and **28**.

FIG. **35** is a cross sectional view of the inner insulator of the plasma generator shown in FIGS. **27** and **28**.

DETAILED DESCRIPTION

FIG. **1** is a schematic view of a heating assembly **10**, according to one embodiment. The heating assembly **10** in the illustrated embodiment generally includes a plasma heat exchanger **12**, an engine driven electrical generator **14** (e.g., a generator with a diesel engine) that supplies electrical current to the plasma heat exchanger, an engine exhaust heat exchanger **16**, an engine coolant heat exchanger **18**, and one or more plasma exhaust heat exchangers **20**. The plasma exhaust heat exchangers **20** receive heated exhaust gases from the plasma heat exchanger **12** for preheating a fluid flowing into the plasma heat exchanger. The engine exhaust heat exchanger **16** receives exhaust gases from the generator's engine for preheating the fluid flowing into the plasma heat exchanger. The engine coolant heat exchanger **18** receives the coolant liquid from the generator's engine and the fluid flowing into the plasma heat exchanger. The inlet fluid to the plasma heat exchanger **12** cools the engine coolant liquid in the engine coolant heat exchanger **18**.

The heating assembly **10** can be used to heat any type of fluid, including without limitation, liquids, such as water, diesel fuel, or kerosene, and gases, such as nitrogen, to name a few. For purposes of description, the heating assembly **10** will be described in the context of heating water, although the assembly can be used to heat other fluids.

In use, water to be heated in the plasma heat exchanger **12** enters the assembly via an inlet conduit **22** (e.g., pipe). A portion of the inlet water can be directed to flow through respective conduits **24**, respective plasma exhaust heat exchangers **20**, and respective conduits **26**, and then into the plasma heat exchanger **12**. Hot exhaust gases from the plasma heat exchanger **12** flow through respective conduits **32**, respective plasma exhaust heat exchangers **20**, and then through an exhaust manifold **34** that exhausts the gases to atmosphere. Inlet water flowing through plasma exhaust heat exchangers **20** therefore is pre-heated by the hot exhaust gas from the plasma heat exchanger.

A portion of the inlet water also can be directed to flow through a conduit **28**, the engine exhaust heat exchanger **16**, a conduit **30**, and then into the plasma heat exchanger **12**. Hot exhaust gases from the generator's engine flows through conduit **36**, the engine exhaust heat exchanger **16**, and then an exhaust conduit **38**, which vents the exhaust gases to atmosphere. Inlet water flowing through the engine exhaust heat exchanger **16** therefore is preheated by the hot exhaust gases from the generator's engine.

A portion of the inlet water also can be directed to flow through a conduit **40**, the engine coolant heat exchanger **18**, a conduit **42**, and then into the plasma heat exchanger **12**. The engine coolant from the generator's engine (e.g., water or a water/antifreeze mixture) circulates through the engine coolant heat exchanger **18** via conduits **44**, **46** to be cooled by the inlet water flowing into the plasma heat exchanger. Inlet water directed into the plasma heat exchanger via conduits **26**, **30**, and **42** is heated by plasma inside the plasma heat exchanger **12**, as described in detail below. Heated water exits the plasma heat exchanger through an outlet conduit **48**, from which the heated water can be directed to one or more users or processes requiring heated water.

FIGS. **2-7** are various views of a specific implementation of the heating assembly **10** shown schematically in FIG. **1**. The components of the heating assembly of FIGS. **2-7** that are the same as the components in FIG. **1** are given the same respective reference numerals and therefore are not repeated here. As best shown in FIG. **7**, the electrical generator **14** includes an engine **50** (e.g., a diesel, natural gas, or gasoline engine) that powers the generator. The generator **14** functions to provide electrical current to the plasma heat exchanger for generating plasma and to power other components of the assembly as needed. As can be appreciated, the use of an engine-driven generator allows the heating assembly **10** to be portable and/or used in applications where an electrical power supply is not readily available. If an electrical power supply is readily available, the generator **14** would not be needed. It also should be noted that any other source of electrical current can be used in place of the generator **14**, such as fuel cells, batteries, etc.

The heating assembly **10** can also include an air compressor **52** (e.g., a rotary screw compressor or reciprocating compressor) that serves as a source of gas supplied to the plasma heat exchanger **12** for generating plasma. The compressed air from compressor **52** can flow through a conventional air/water separator **56**, and into a compressed air storage tank **54**. As best shown in FIGS. **2** and **4**, compressed air in the tank **54** is supplied to the plasma heat exchanger via compressed air conduits **64**, as further described below. The compressor **52** can be powered by electrical current from the generator **14** or another convenient power source. The air compressor **52** can also be replaced by any convenient source of a compressed gas that can be used in the generation of plasma. For example, the plasma heat exchanger can be supplied with an inert gas (e.g., helium, argon) from an inert gas source (e.g., a storage tank) if one is readily available.

In an alternative embodiment not shown in FIGS. **2**-**7**, an air dryer can be fluidly connected to the separator **56** and the tank **54**. In this alternative embodiment, compressed air from the compressor **52** can flow first through the separator **56**, then through the dryer, which removes all or substantially all water vapor from the compressed air. After passing through both the separator **56** and the dryer, the compressed air can then flow into the tank **54**. While many commercially available air dryers may be used, one that has been found to be suitable is the Ingersoll Rand HL400 Series desiccant air dryer.

The heating assembly **10** can also include water pumps **58** placed in the inlet water conduits **22**. As best shown in FIGS. **3** and **7**, pressurized water from pumps **58** flow through conduits **22**, a manifold **60**, where it is distributed to conduits **24**, **28**, and **40**. In the embodiment illustrated in FIGS. **2**-**7**, the components of the heating assembly **10** are arranged together on a frame. In an alternative embodiment, however, the components are not all arranged together in such a fashion and at least one of the components (e.g., the generator **14** or the air compressor **52**) is provided in a location remote from the remainder of the assembly. In this alternative embodiment, wires, tubes, or other appropriate connecting elements are used to connect each of the remote components to the remainder of the assembly.

FIG. **8** shows an exploded view of the plasma heat exchanger **12**. The plasma heat exchanger **12**, in the illustrated embodiment, comprises a nozzle plate **100**, a burner housing **102**, a coil housing **104**, a diverter **106**, an exit plate **108**, an exit flange **110**, an outlet manifold **112**, one or more plasma generators **114** (also referred to as plasma torches or plasma nozzle assemblies), one or more gaskets **116**, one or more heat sinks **118**, one or more seals **120**, one or more burn chambers **122** disposed in the burner housing **102**, one or more coils **124** disposed in the coil housing, and a support ring **126** that supports the diverter **106** within the coil housing **104**.

The nozzle plate **100** includes one or more apertures **128**, each of which is sized to receive and support a respective plasma generator **114**. As best shown in FIGS. **9** and **9**A, each plasma generator **114** extends through a corresponding aperture **128** and partially into a respective burn chamber **122**. The inflow end of each burn chamber **122** (the end closest to the nozzle plate **100**) is connected to the nozzle plate **100** with a heat sink **118**. A gasket **116** (or equivalent sealing element) can be positioned between each heat sink **118** and the inside surface of the nozzle plate **100**. Another gasket **120** (or equivalent sealing element) can be positioned between each heat sink **118** and an end flange **144** of an adjacent burn chamber **122**. Each plasma generator **114** can be secured to the nozzle plate **100** and a burn chamber **122** by a plurality of bolts **142** that extend through the plasma generator **114**, the nozzle plate **100**, a respective gasket **116**, a respective heat sink **118**, and an end flange **144** of the respective burn chamber **122**.

Each plasma generator **114** receives compressed air from the compressor **52** (or compressed gas from another source) and electrical current from the generator **14** (or another current source) to generate plasma, which is directed into respective burn chambers **122**. Each burn chamber **122** is in fluid communication with a respective coil **124** that receives plasma and/or heated exhaust gases from the burn chamber. Each coil **124** can have an end portion **138** that extends through a corresponding aperture **140** in end plate **108** and is fluidly connected to a respective conduit **32** (FIG. **5**) that directs heated exhaust to flow into respective plasma exhaust heat exchangers **20** (FIG. **5**). Each burn chamber **122** and respective coil **124** collectively form a conduit that receives plasma and/or hot exhaust gases used to heat a liquid in the plasma heat exchanger **12**. In an alternative embodiment, the coil **124** or a portion thereof can be a straight, non-coiled conduit.

The burner housing **102** includes one or more inlet openings **130** (three in the illustrated embodiment) spaced in the circumferential direction around the outer surface of the housing. Each opening **130** is fluidly connected to a respective conduit **26** (FIG. **1**). Thus, the fluid to be heated (e.g., water) flows through conduits **26** and into the housing **102** via openings **130**. The housing **102** can further include secondary openings **132** that receive fluid to be heated from conduits **30** and **42**. Fluid entering the heat exchanger via openings **130**, **132** flows through the burner housing and over the burner chambers **122**, and then upon entering the coil housing **104**, the diverter **106** causes the fluid to flow radially toward the inner surface of the coil housing so as to flow over the coils **124** (as indicated by arrows **136**). At the rear end of the coil housing, the fluid flows outwardly through outlet conduits **134** and into outlet manifold **112**.

Referring to FIGS. **10** and **11**, the plasma generator **114** will now be described in greater detail. The plasma generator **114** in the illustrated embodiment comprises a nozzle housing **160**, an air injection cap **162**, an end plate **164**, a nozzle **166** disposed partially in the housing **160**, an electrode **168** centrally positioned within the nozzle **166**, an outer insulator **170** disposed between the housing **160** and the nozzle **166**, and an inner insulator **172** disposed between the electrode **168** and the nozzle **166**. The electrode **168** serves as the anode of the plasma generator and the nozzle **166** serves as the cathode of the plasma generator. In use, the two sides of an electrical potential source are electrically connected to these components to establish an electric arc.

The air injection cap **162** can be secured to the nozzle **166** by a plurality of bolts **174** that extend through corresponding openings in the cap **162** and are tightened into corresponding openings in an end flange **178** of the nozzle **166**. The electrode **168** can be secured to air injection cap **162** by a central bolt **176** that extends through an opening in the cap **162** and is tightened in a central opening in the electrode **168**. As best shown in FIGS. **11** and **13**, the air injection cap **162** can be secured to the nozzle housing **160** by a plurality of bolts **184** that extend through corresponding openings in the cap **162** and are tightened in corresponding openings in the nozzle housing **160**.

The air injection cap **162** includes an inlet conduit **180** that is fluidly connected to a source of compressed gas (e.g., compressed air). In the illustrated embodiment, for example, the inlet conduit **180** is connected to a compressed air line **64** that supplies compressed air from tank **54** to the plasma generator **114**. As best shown in FIGS. **14-16**, the air injection cap **162** includes a side opening **182** that extends from the outer surface of the cap to an internal space **186** of the cap. The inlet conduit **180** extends into the side opening **182** so that compressed gas flows through the opening **182** and into the internal space **186** of the air injection cap **162**.

The air injection cap **162** can further include a slot **194** that extends all the way through the side wall of the air injection cap. A conductor bar **196** (FIGS. **12** and **13**) is inserted into and through the slot **194** so as to physically and electrically contact the end surface of the electrode **168** (FIG. **10**). The air injection cap **162** can also be formed with a recessed portion **198** that receives the head of a bolt **200** (FIG. **13**). The bolt **200** extends through the air injection cap **162** and is tightened into a corresponding opening **202** (FIG. **23**) in the flange **178** of the nozzle **166**. A first cable or other electrical conductor (not shown) electrically connected to the positive side of the generator **14** is connected to the conductor bar **196** and a second cable or other electrical conductor (not shown) electrically connected to the negative side of the generator **14** is connected to the bolt **200**. In this manner, the electrode **168** can be placed in electrical contact with the positive side of the generator and the nozzle **166** can be placed in electrical contact with the negative side of the generator.

As best shown in FIGS. **17-19**, the inner insulator **172** comprises a central opening **188** that receives the electrode **168** and a plurality of longitudinally extending, outer openings **190** that are angularly spaced about the central opening **188**. As shown in FIG. **10**, the openings **190** are aligned with internal space **186** of the air injection cap **162** and allow compressed gas to flow through the insulator **172**. As best shown in FIGS. **20-22**, the outer insulator **170** comprises a central opening **192** sized to fit around the nozzle **166**. The insulators **170**, **172** help insulate the nozzle housing and adjacent components of the heat exchanger **12** from the heat generated inside the plasma generator **114**. The insulators **170**, **172** can be made of alumina or any of various other suitable materials. In one example, the insulators are made of 99% alumina.

As best shown in FIG. **9**A, the nozzle generators **114** are mounted to the nozzle plate **100** such that the nozzle housing **160** and the nozzle **166** extend partially into the burner housing **102**. A heat sink **118** is co-axially mounted around the portion of each nozzle housing extending into the burner housing. As best shown in FIGS. **25** and **26**, the heat sink **118** can comprise an annular ring shaped structure comprising a central opening **206** adapted to receive a nozzle housing **160** and a plurality of axial spaced, annular fins **208**. The heat sinks **118** assist is transferring heat from the plasma generators **114** to the surrounding fluid. Thus, the heat sinks **118** help promote heating of the fluid in the burner housing **102** and help cool the plasma generators **114** to keep them below the desired operating temperature.

In one specific embodiment, the various components of the heat exchanger **12** and the nozzle generator **114** are made of the following materials. The air injection cap **162** and the end plate **164** are made of polytetrafluoroethylene (PTFE). The nozzle **166** and the electrode **168** are made of a copper-tungsten alloy. The inner and outer insulators **172**, **170**, respectively, are made of 99% alumina. The housing **160** is made of 316L stainless steel. The conductor bar **194** is made of copper. The burner housing **102**, the coil housing **104**, the diverter **106**, the burn chambers **122**, the coils **124**, the outlet pipe **112**, and the heat sinks **118** are made of stainless steel, such as 316L or 310L stainless steel.

Referring to FIGS. **27-35**, an alternative plasma generator **300** will now be described. Multiple plasma generators **300** can be used in place of the plasma generators **114** within the heat exchanger **12**. The plasma generator **300** in the illustrated embodiment comprises a housing **302** and an air and water injection cap **304**. The housing **302** houses several nested cylindrical components including an outer insulator **306** in contact with the inner surface of the housing **302**, a cathode **308** in contact with the inner surface of the outer insulator **306**, an inner insulator **310** in contact with the inner surface of a cathode **308**, and an anode **312** in contact with the inner surface of the inner insulator **310**. An electrical potential difference is established between the cathode **308** and the anode **312** when connected to a source of electricity, and thus an electric arc can be generated in the air passing between them.

The outer insulator **306** is generally cylindrically shaped and comprises an insulating material. As best seen in FIGS. **29-31**, the cathode **308** is generally cylindrically shaped and includes a system of ducts or channels to allow a coolant fluid to flow through its structure. In the illustrated embodiment, the cathode **308** includes four ducts or channels, each projecting axially through the interior of the cathode **308**. As illustrated, two inflow ducts **316** carry water (or another coolant fluid) into the cathode from a water source, while two outflow ducts **318** receive water from the inflow ducts **316** via channels **320** and carry the water out of the cathode **308**. Each channel **320** extends between and fluidly connects an inflow duct **316** to a respective outflow duct **318**. As best shown in FIG. **35**, the inner insulator **310** is generally cylindrically shaped and, as illustrated, includes six air channels **314** for carrying air through the plasma generator **300**.

As best illustrated in FIGS. **32-34**, the anode **312** is generally cylindrically shaped and includes a larger diameter cylindrical portion **322**, a transition portion **324**, a smaller diameter cylindrical portion **326**, a water inlet extension **328** and a water outlet extension **330**. The anode **312** further comprises an inlet duct or channel **332** and an outlet duct or channel **334**, each extending through the larger cylindrical portion, one transfer duct or channel **336** extending through the transition portion **324**, and one distal channel **338** in the smaller cylindrical portion **326**. The water inlet extension **328**, the inlet duct **332**, the transfer duct **336**, the outlet duct **334**, and the water outlet extension **330** are in fluid communication such that a pressurized fluid introduced into the water inlet extension **328** will flow through the inlet duct **332** along the length of the larger diameter portion **322**, through the transfer duct **336**, back through the outlet duct **334** along the length of the larger diameter portion **322**, and exit through the water outlet extension **330**. The anode **312** can be fabricated either by machining from a solid piece of material (FIG. **34**), or by casting (FIGS. **32-33**). A cylindrical slug **340** may be positioned in the distal channel **338**. The slug **340** can comprise, as one specific example, halfnium coated in silver, and may aid in transferring heat energy from plasma generation from the smaller cylindrical portion **326** to the water or other coolant fluid carried through the transfer duct **336**. As shown, the slug **340** can be positioned such that an end portion of the slug extends into the transfer duct.

In the illustrated configuration, pressurized water can be provided to and withdrawn from the various ducts in the anode and the cathode via conduits through the injection cap **304**. The provision of flowing water helps insulate and protects against overheating of the anode **312** and cathode **308**, which carry electric current for the generation of plasma. Also in this configuration, air for generating plasma is provided via conduits through the injection cap **304** to the air channels **314**, which carry the air through the plasma generator.

In one specific embodiment, the components of the plasma generator **300** are made of the following materials. The injection cap **304** is made of PTFE. The cathode **308** and anode **312** are made of a copper-chromium alloy. The inner insulator **310** and the outer insulator **306** are made of 99% alumina, and the housing **302** is made of stainless steel such as grade 303 stainless steel.

Referring again to FIG. **10**, to generate plasma, an electrical potential difference is established between the electrode **168** and the nozzle **166**, which causes an electric arc to be established across the radial gap **214** between the end portion of the electrode **168** and the surrounding portion of the nozzle **166**. Compressed air (e.g., compressed air at 20 psig) supplied to the air injection cap **162** flows through the nozzle **166** as indicated by arrows **210**. As the compressed air crosses the electric arc, the air is ionized, creating plasma, or a plasma arc, which is discharged outwardly through the outlet opening **212** of the nozzle and into the respective burner chamber **122**. The fluid to be heated in the heat exchanger **12** (e.g., water) flows over the burner chambers **122** and the coils **124** and therefore is heated by the heat of plasma and exhaust gases in the burner chambers and the coils.

The frequency of the power supply to the plasma generators can be adjusted to vary the electric arc between the electrode **168** and the nozzle **166**. In particular, increasing the frequency above 60 Hz, to about 80-85 Hz or greater, can increase the frequency of sparks across the gap **214** to form a substantially annular electric arc extending between the electrode **168** and the nozzle **166**, which promotes the generation of plasma from the air crossing the electric arc. The frequency of the power supply can be increased in some embodiments to at least 100 kHz, and in some embodiments up to 50 GHz.

The assembly **10** can further include a controller to control the operation of the various components of the assembly, including the generator **14**, the air compressor **52**, the pumps **58**, and the plasma generators **114**. The controller can be programmed (such as by user input) to set various operating parameters, such as the voltage, current and frequency of power supplied to each plasma generator and the operating sequence of each plasma generator. For example, each plasma generator **114** can be cycled on and off in a predetermined sequence with the other plasma generators to avoid overheating of the generators. In a specific implementation, for example, only one plasma generator is cycled on while the other two are cycled off. Initially, each plasma generator is cycled on for a period of about 5-7 seconds and then for a period of about 3 seconds for each subsequent cycle. It should be noted that the operating parameters of the generators **114** (including the operating sequence and frequency) can be varied depending on the specific application.

In a specific application, the heating assembly **10** is used to heat a cleaning fluid for treating a well bore or pipeline used in the transfer of hydrocarbon fluids, such as oil and gas. In the transfer and production of hydrocarbon fluids, well bores, pipelines and other conduits become clogged and/or fouled from accumulation of various compounds. A known technique for cleaning well bores and pipelines involves heating a solution and injecting the solution into the well bore and/or pipeline. A known heating system used for this purpose utilizes friction heating to heat about 4,800 gallons of water per hour to about 250 degrees F. The assembly **10** of the present disclosure can be used to heat about 18,000 gallons of water per hour from ambient (about 68 degrees F.) to about 290 degrees F. The heating assembly **10** can also be used to heat any of various other fluids, such as diesel fuel and kerosene, for cleaning well bores and pipelines. The heated fluid can also be used for fracking in which the fluid is injected into a well bore under pressure to create fractures in underground rock formations, such as shale rock and coal beds.

In another application, the heating assembly can be used to heat nitrogen for use in fracking. In such an application, liquid nitrogen stored in a tank (which can be on or adjacent the heating assembly) is supplied to an expansion chamber, which allows the nitrogen to expand into a gas. From the expansion chamber, the nitrogen flows into the plasma heat exchanger and is heated to at least about 85 degrees F. The heated nitrogen exiting the heat exchanger can be pressurized and injected into a well bore for fracking, as known in the art. In another embodiment, the nitrogen can be fed into the plasma generators **114** (instead of the compressed air) to create high temperature plasma from the nitrogen. The nitrogen cools to an appropriate working temperature and then can be pressurized and injected into a well bore.

The heating assembly **10** can also be used in a variety of other applications. For example, the heating assembly can be used in a variety of different industrial processes requiring a relatively large supply of a heated fluid, for heating a building, or for rapidly boiling water. In alternative embodiments, a plasma generator **114** can be used apart from the heat exchanger **12** for a variety of applications where heat from plasma can be utilized. For example, the plasma generator **114** can be used as a plasma torch for cutting metal, burning or incinerating material, such as trash or waste, or for various other uses.

In view of the many possible embodiments to which the principles of the disclosed invention may be applied, it should be recognized that the illustrated embodiments are only preferred examples of the invention and should not be taken as limiting the scope of the invention. Rather, the scope of the invention is defined by the following claims. I therefore claim as my invention all that comes within the scope and spirit of these claims.

I claim:

1. A heating apparatus for heating a fluid comprising:

a plasma generator;

a conduit extending from the plasma generator and configured to receive plasma and/or plasma exhaust from the plasma generator;

a conduit housing surrounding the conduit and having an inlet and an outlet, wherein a fluid to be heated can flow into the conduit housing via the inlet, over the conduit, and out of the conduit housing via the outlet, wherein the fluid flowing over the conduit is heated by the plasma and/or plasma exhaust in the conduit;

wherein the conduit comprises a burn chamber and a coil, the burn chamber extending from the plasma generator and configured to receive plasma from the plasma generator, wherein the coil extends from the burn chamber and is configured to receive plasma and/or plasma exhaust from the burn chamber;

wherein the plasma generator comprises at least three plasma generators;

wherein the conduit comprises at least three conduits, each comprising a burn chamber and a coil, wherein each burn chamber extends from a respective one of the three plasma generators and is configured to receive plasma from the respective one of the three plasma generators;

wherein each coil extends from a respective one of the three burn chambers and is configured to receive plasma and/or plasma exhaust from the respective one of the three burn chambers, and wherein the conduit housing surrounds each of the three conduits; and an insert positioned within the conduit housing, wherein the three coils are positioned between an inner surface of the conduit housing and an outer surface of the insert, wherein each coil extends around the outer surface of the insert.

2. The apparatus of claim **1**, wherein:

each plasma generator extends partially into one of the burn chambers; and

the apparatus further comprises a heat sink mounted co-axially on each plasma generator and positioned within the housing.

3. The apparatus of claim **1**, further comprising:

an electrical power supply, wherein the electrical power supply supplies electrical power to the plasma generators; and

an air compressor, wherein the air compressor feeds compressed air to the plasma generators.

4. The apparatus of claim **3**, further comprising a controller unit configured to control a voltage, a current, and a frequency of the electrical power supplied to the plasma generators.

5. The apparatus of claim **4**, wherein the electrical power supply comprises an electrical generator having an engine.

6. A heating apparatus for heating a fluid comprising:

a plasma generator;

a conduit extending from the plasma generator and configured to receive plasma and/or plasma exhaust from the plasma generator;

a conduit housing surrounding the conduit and having an inlet and an outlet, wherein a fluid to be heated can flow into the conduit housing via the inlet, over the conduit, and out of the conduit housing via the outlet, wherein the fluid flowing over the conduit is heated by the plasma and/or plasma exhaust in the conduit;

an electrical power supply, wherein the electrical power supply supplies electrical power to the plasma generator;

an air compressor, wherein the air compressor feeds compressed air to the plasma generator;

a controller unit configured to control a voltage, a current, and a frequency of the electrical power supplied to the plasma generator;

wherein the electrical power supply comprises an electrical generator having an engine;

an engine exhaust heat exchanger configured to exchange heat between an exhaust produced by the engine and the fluid before the fluid flows into the conduit housing;

an engine coolant heat exchanger configured to exchange heat between a coolant used by the engine and the fluid before the fluid flows into the conduit housing; and

a plasma exhaust heat exchanger configured to exchange heat between an exhaust received from the outlet of the conduit and the fluid before the fluid flows into the conduit housing.

7. The apparatus of claim **6**, wherein a portion of the conduit has a coiled configuration.

8. The apparatus of claim **1**, wherein each plasma generator comprises:

a casing;

an outer insulator positioned coaxially within the casing;

a cathode positioned coaxially within the outer insulator;

an inner insulator positioned coaxially within the cathode; and

an anode positioned coaxially within the inner insulator.

9. A method of heating a fluid using the heating apparatus of claim **1**, the method comprising:

generating plasma within each burn chamber; and

allowing the fluid to flow through the housing and over each burn chamber, thereby receiving heat from the plasma.

10. The method of claim **9**, wherein generating plasma comprises cyclically operating the plasma generators such that each plasma generator alternates between generating plasma and not generating plasma.

11. The method of claim **10**, wherein the cycles of each of the plurality of plasma generators are coordinated such that plasma is constantly generated by the plurality of plasma generators.

12. The method of claim **9**, wherein the fluid flows through an annular flow path between the burn chambers and the housing.

13. The apparatus of claim **8**, wherein:

the inner insulator includes air channels extending along its length;

the cathode includes at least one inflow channel and at least one outflow channel for passing a coolant therethrough; and

the anode comprises at least one internal coolant path comprising at least one inflow channel and at least one outflow channel for passing a coolant therethrough.

14. The apparatus of claim **13**, wherein:

the anode further comprises a slug of heat-conducting material positioned at least partially within the coolant path.

15. The apparatus of claim **14**, further comprising a heat sink mounted co-axially on the casing, the heat sink comprising a plurality of spaced apart fins.

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